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Variability of aerosol and spectral lidar and backscatter and extinction ratios of key aerosol types derived from selected Aerosol Robotic Network locations

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[1] The lidar (extinction-to-backscatter) ratios at 0.55 and 1.02 μm and the spectral lidar, extinction, and backscatter ratios of climatically relevant aerosol species are computed on the basis of selected retrievals of aerosol properties from 26 Aerosol Robotic Network (AERONET) sites across the globe. The values, obtained indirectly from sky radiance and solar transmittance measurements, agree very well with values from direct observations. Low mean values of the lidar ratio, S_a, at 0.55 μm for maritime (27 sr) aerosols and desert dust (42 sr) are clearly distinguishable from biomass burning (60 sr) and urban/industrial pollution (71 sr). The effects of nonsphericity of mineral dust are shown, demonstrating that particle shape must be taken into account in any spaceborne lidar inversion scheme. A new aerosol model representing pollution over Southeast Asia is introduced since lidar (58 sr), color lidar, and extinction ratios in this region are distinct from those over other urban/industrial centers, owing to a greater number of large particles relative to fine particles. This discrimination promises improved estimates of regional climate forcing by aerosols containing black carbon and is expected to be of utility to climate modeling and remote sensing communities. The observed variability of the lidar parameters, combined with current validated aerosol data products from Moderate Resolution Imaging Spectroradiometer (MODIS), will afford improved accuracy in the inversion of spaceborne lidar data over both land and ocean.

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1. Introduction

[2] The geographical and temporal variability of aerosols dictate the use of long-term detailed global measurements from satellites and Earth's surface to accurately assess their impact on the global climate [*Kaufman et al.*, 1997a]. Advances in radiometric measurements from space and ground have now afforded a view of the global aerosol system [*Kaufman et al.*, 2002] and recognition of several key aerosol species that affect global climate (biomass burning, desert dust, sea salt, pollution). Ground-based remote sensing, in particular, has evolved to become a powerful method for characterizing the suspended aerosol [*Dubovik and King*, 2000], such that a clearer picture of the optical properties of each of these aerosol species is emerging [*Dubovik et al.*, 2002a]. Passive spaceborne measurements presently employ such models in their processing schemes [*Tanré et al.*, 1997; *Vermote et al.*, 1997], and both ground- and space-based aerosol data products are used to evaluate the performance of general circulation models [*Chin et al.*, 2002; *Kinne et al.*, 2003].

[3] Active lidar systems contribute to the global climate effort through their ability to determine the vertical profiles of aerosol extinction and backscattering, which must be known to reduce uncertainty in the aerosol forcing of climate [*Hansen et al.*, 1997; *Haywood and Boucher*, 2000]. This is particularly important in the case of light-absorbing black carbon, where climatic effects of pollution can be felt on a regional scale [*Menon et al.*, 2002; *Sato et al.*, 2003]. Spaceborne lidar, such as the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) sensor expected to launch in 2005, thus promises to improve our understanding of aerosol properties and distribution on both a global and regional basis.

[4] Currently, space-based retrieval of vertical profiles of aerosol extinction and backscatter coefficients necessitates the prescription of their ratio, commonly called the lidar ratio, S_a. The accuracy of this prescribed ratio determines the accuracy of the retrieved profiles. While a number of height-resolved lidar ratio observations have been made using special types of ground-based lidar or by combinations of instruments at the surface, these are insufficient in time or space to give a global climatology of S_a values. A

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measure of the variability in S_a of key aerosol types around the world would prove useful to inverting global lidar observations.

[5] In this paper, we employ ground-based retrievals of aerosol properties from the global aerosol network AERONET [*Holben et al.*, 1998] for several key aerosol types (biomass burning, mineral dust, oceanic and anthropogenic pollution) to quantify the variability in lidar ratios at 0.55 and 1.02 μm and spectral backscatter and extinction ratios. Careful selection of the geographic location and time of year based upon known seasonal events helped isolate retrievals where a single aerosol species dominated the atmospheric column. The use of 26 worldwide sites provides a fairly robust picture of the natural variability within each aerosol species over a global scale. We then compare these values to those found in the literature and draw some preliminary conclusions on how the use of spectral lidar ratios, combined with backscatter and extinction ratios, can discriminate the aerosol types. The effect of particle nonsphericity upon the lidar parameters is explored through a combination of modeling and comparison with field measurements. Radiometric satellite measurements over the ocean have been shown to enhance the information retrieved by spaceborne lidar [*Kaufman et al.*, 2003; *Leon et al.*, 2003]. We also explore in this paper ways to retrieve aerosol vertical profiles over both land and ocean using validated aerosol data products of MODIS and AERONET.

2. Theory

2.1. Lidar Equation

[6] The range- and energy-normalized signal of a returned lidar pulse, $X(r)$, can be expressed by

$$X(r) = C\beta(r)T^2(r), \tag{1}$$

where C is a calibration constant, which depends upon factors such as transmitted power; receiver cross section; efficiency of the detector and optical system; and corrections for near-range field-of-view problems, $\beta(r)$ is the volume atmospheric backscattering coefficient, and $T^2(r)$ represents the total round-trip transmittance to range r, such that

$$T^2(r) = T_a^2(r)T_R^2(r) = e^{-2\int[\sigma_a(r')+\sigma_R(r')]dr'}, \tag{2}$$

$$\beta(r) = \beta_a(r) + \beta_R(r). \tag{3}$$

The subscripts a and R represent aerosol and molecular (Rayleigh) atmospheric components, respectively, and σ represents the unit volume extinction coefficient. The backscatter solution to the above nonlinear equation, obtained using a modeled value for the lidar ratio (S_a), is given by [*Fernald*, 1984; *Fernald et al.*, 1972],

$$\beta_a(r) = \frac{X(r)e^{-2(S_a-S_R)\int_{r_c}^{r}\beta_R(r')dr'}}{\frac{X(r_c)}{\beta_a(r_c)+\beta_R(r_c)} - 2S_a\left[\int_{r_c}^{r} X(r)e^{-2(S_a-S_R)\int_{r_c}^{r}\beta_R(r')dr'}dr'\right]} - \beta_R(r), \tag{4}$$

where r_c is a Rayleigh reference calibration range; i.e., where $\beta(r_c) \approx \beta_R(r_c)$, and

$$S_a = \frac{\sigma_a(r)}{\beta_a(r)} \text{ and } S_R = \frac{8\pi}{3}. \tag{5}$$

Hence the extinction solution is also obtained by $\sigma_a(r) = S_a \cdot \beta_a(r)$.

[7] The aerosol lidar ratio can vary widely depending on aerosol size distribution and refractive index [*Ackermann*, 1998; *Barnaba and Gobbi*, 2004] but, in the absence of auxiliary or lidar self-determined transmittance information, must be specified before the vertical profiles of the extinction and backscattering coefficients can be determined.

6. Conclusion

[34] Several thousand inversions of AERONET data satisfying stringent quality requirements have been used to determine the variability in lidar, backscattering, and extinction ratios of five distinct aerosol species. The careful selection of geographic location and season in the analysis led to a robust climatology of lidar ratios that agrees extremely well with direct field measurements for all aerosol species considered. This indicates that global distributions of assumed regions of aerosol species, by season, may in itself lead to reasonably accurate predictions of S_a for the purpose of inverting lidar observations on a global basis. The wavelengths used in the analysis were near those possessed by the upcoming spaceborne lidar CALIPSO mission, which allows their direct application to active remote sensing from space. Spectral lidar parameters such as the backscattering and extinction ratios promise to further improve the accuracy of the retrievals of aerosol properties from multiwavelength lidar observations such as those anticipated from CALIPSO.

[35] Use of simultaneous passive radiometer measurements (e.g., Angstrom exponent) can further refine the choice of lidar ratio used to invert CALIPSO data. The similarity in aerosol types in this study with those of the MODIS aerosols over land suggests that the MODIS data product of aerosol type over land can be used with reasonable confidence to select the lidar ratio over land. With the more precise information on spectral optical depth obtained from radiometric measurements over the ocean, accurate selection of S_a should be possible over much of the Earth's surface.

[36] The use of spheroids to predict the optical properties of nonspherical particles increases the lidar ratio of mineral dust by a factor of over 2.5 from the lidar ratio computed assuming spheres, and produces results that agree surprisingly well with field and surface measurements. This finding clearly indicates that the nonsphericity of mineral dust must be taken into account in spaceborne lidar retrievals.

[37] Last, it is evident that regional consideration of the sources of black carbon aerosols is desirable to more accurately retrieve the vertical profiles of their properties using space-based lidar. This could perhaps be achieved through use of emission inventories or level of industrial development. The results of this study indicate that accounting for the distinct differences in properties of polluting aerosols from different geographic regions would improve the monitoring of pollution sources and estimates of the radiative forcing by black carbon aerosols.